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AMMONIA EMISSIONS OF PULLETS AND LAYING HENS AS AFFECTED BY STOCKING DENSITY AND MANURE ACCUMULATION TIME

L. B. Mendes, H. Xin, H. Li

ABSTRACT. Data on ammonia (NH_3) emissions from pullets (hens <18 weeks of age) are non-existent despite the large differences in nutritional and environmental conditions between raising pullets and laying hens. Different stocking densities (SDs) in housing the birds may be used according to certain industry guidelines on production; however, information concerning the impact of SD on properties of accumulated manure and thus NH_3 emissions is limited in the literature. It was hypothesized that bird SD affects the amount of manure per unit of storage or surface area as manure accumulates, and the exposed manure surface area may in turn affect NH_3 emission from the accumulated manure. A lab-scale study was conducted that resembled the conditions of manure-belt laying-hen houses with the objectives of (1) determining the magnitude of NH_3 emission rate (ER) of pullets (W-36 breed) as a function of age, and (2) assessing the effect of SD on NH_3 ER of pullets and laying hens during a 6-day manure accumulation time (MAT). Two SDs at a given bird age (4 to 37 weeks) were evaluated, ranging from 155 and 206 cm^2 to 413 and 620 cm^2 (24 and 32 in.^2 to 64 and 90 in.^2) per bird, designated as high density (HD) and low density (LD), respectively. Ammonia ER was expressed on the basis of per bird, per animal unit (AU, 500 kg live body weight), per kg of feed nitrogen (N) use, and per kg of as-is or dry manure. Results showed that daily NH_3 ER for pullets and laying hens increased exponentially with bird age and MAT ($p < 0.0001$). Compared to the HD regimen, the LD regimen had 51% lower NH_3 ER (in $\text{mg bird}^{-1} \text{d}^{-1}$) for 4- to 5-week-old pullets and averaged 22% lower for laying hens. Results of this study provide a scientific basis concerning the impact of certain management practices on NH_3 emissions and offer insight into reducing NH_3 emissions from egg production operations.

Keywords. Ammonia emission, Laying hen, Manure accumulation, Pullets.

Animal feeding operations (AFOs) are associated with aerial emissions, primarily ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO), methane (CH_4), hydrogen sulfide (H_2S), volatile organic compounds (VOCs), and particulate matter (NRC, 2003). Aerial emission rate (ER) is the product of source concentration of the substance and the air exchange rate through the source.

Among all constituents emitted from poultry production facilities, NH_3 is the predominant noxious gas due to the nature of the manure (Yang et al., 2000). Livestock and poultry are often fed high-protein diets, which contain surplus nitrogen, to ensure that the animals' nutritional requirements are met. Nitrogen that is not metabolized into animal protein or product is excreted as urea in the urine of

cattle and swine or as uric acid from poultry where further microbial action releases NH_3 into the air during manure decomposition (Gay et al., 2009). The NH_3 volatilization rate from solid poultry manure is affected by nitrogen content, moisture content, surface area to volume ratio (and hence the stacking configuration of the manure pile), pH, temperature, and oxygen availability, all of which contribute to the microbial activity and NH_3 release from the manure (Li, 2006). Research has shown that prolonged exposure to high levels of NH_3 can cause reduced body weight gain and egg production in laying hens and can also have a detrimental impact on farm workers (Carlile, 1984; Ning, 2008).

The most recent studies on NH_3 emissions from commercial U.S. poultry operations include those reported by Liang et al. (2005) for laying hens, Wheeler et al. (2006) and Burns et al. (2007) for broilers, and Li et al. (2011) for turkeys. A national study through an air compliance agreement (ACA) between the U.S. EPA and certain sectors of the livestock and poultry industry has been completed (data analysis in progress at the time of this writing) that aims to collect more baseline data on AFO air emissions (USEPA, 2011). Laboratory experiments performed by Ning (2008) showed that NH_3 ER from laying hens depends on manure accumulation time (MAT). Ning (2008) also found that the emissions had an inverse relation to defecation events. Moreover, hens may be housed at different stocking densities as producers respond to certain industry production management guidelines, such as those by the United Egg Producers and/or fast-food restaurant chains (e.g., McDon-

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ald's). Hence, there is a need to quantify the impact of bird stocking density (SD) on aerial ER.

The objectives of this study were (1) to delineate the magnitude of NH_3 ER of pullets and laying hens vs. bird age and MAT, and (2) to assess SD effects on NH_3 ER of pullets and laying hens. Results from this research will help fill a literature gap on pullet NH_3 emission and provide insight into the impact of production management practices (i.e., MAT and SD) on NH_3 emissions.

METHODOLOGY

DYNAMIC GAS EMISSIONS MEASUREMENT SYSTEM

The study was conducted using four dynamic gas emissions measurement chambers at the Iowa State University Livestock Environment and Animal Physiology Laboratory II (LEAP Lab II). The chambers each had dimensions of 86 cm length \times 45 cm width \times 66 cm height and were located inside an environmentally controlled room. The chamber walls were constructed with 5 mm transparent plexiglass panels. Inside each chamber was a metal-framed wire-mesh cage (44 cm length \times 34 cm width \times 58 cm height). Fresh air to each chamber was supplied through an air distribution plenum to improve spatial uniformity, and the air supply was powered with a diaphragm air pump (100 L min^{-1} capacity, DDL 120-101, Gast Manufacturing, Inc., Benton Harbor, Mich.) placed on the inlet side of the chamber, thereby creating a positive-pressure ventilation system. The airflow rate through each chamber was measured with a thermoelectric air mass flow meter (capacity of 110 L min^{-1} , GFM57, Aalborg Instruments and Controls, Inc., Orangeburg, N.Y.) placed in the supply air stream. Airflow through each chamber was adjustable via a bypass valve so that the concentration of target gases (NH_3 and CO_2) inside the chamber could be controlled. One air temperature and relative humidity (RH) sensor (HMP45A/D, Vaisala, Woburn, Mass.) was placed in each chamber to measure dry-bulb temperature and RH. A plastic cup with tubing was placed underneath each nipple drinker to catch and divert any water leakage out of the manure pan or chamber.

The feeder was made of a stainless steel container (15 cm length \times 10 cm width \times 15 cm depth) that had a 1 cm edge (lip) folded inward at the top frontal face to reduce feed wastage. An adjustable square acrylic stand was placed underneath the feeder to achieve the desirable feeder height for birds at different ages. In order to minimize feed wastage during feeding, a 9 cm length \times 14 cm width wire screen (opening of 2.24 cm \times 2.24 cm) was placed on top of the feed. In addition, all feed spilled out of the feeder that remained in the chamber bottom was collected and weighed once a week, and subsequently subtracted in the feed intake determination.

To capture feeding and defecation events of the birds, two electronic balances (2200.0 g \pm 0.1 g, model GX2000, A&D Co. Ltd., Tokyo, Japan) with a 0 to 2.2 VDC analog output (sampling rate of 1 s) were used in each chamber. One balance was used for measurement of the feeder weight or feeding activities, and the other was used for measurement of the manure pan weight or defecation activ-

ities. Feed use and as-is manure production were calculated as the difference in the scale weight between the beginning and end of each day.

Samples of the exhaust air from each chamber were successively taken using a sampling pump (capacity of 20 L min^{-1} , model 2107CA20B TEFL, Gardner Denver, Inc., Sheboygan, Wisc.) at 5 min intervals, with the first 3 min for stabilization and the last 2 min for measurement. This sampling sequence yielded a measurement cycle of 25 min for the entire system (including 5 min for the ambient air). The successive sampling was accomplished through controlled operation of five solenoid valves (PKV-2R-D1/4NF, Takasago Electric, Inc., Nagoya, Japan). A Teflon filter (4.7 cm diameter, 5 μm pore diameter) connected to Teflon tubing (0.63 cm inside diameter) was placed in front of each solenoid valve. A photoacoustic multi-gas analyzer (model 1412, Innova AirTech Instruments A/S, Ballerup, Denmark) was used to measure NH_3 and CO_2 concentrations. The multi-gas analyzer was challenged weekly and calibrated, as needed, with zero, 25 ppm NH_3 (balanced with air) and 2500 ppm CO_2 (N_2 balance) span calibration gases. Dewpoint temperature of the air samples was measured with a dewpoint hygrometer (model 2001, EdgeTech, Marlborough, Mass.).

Analog outputs from the temperature sensor, multi-gas analyzer, dewpoint hygrometer, electronic balances, and mass flowmeters were logged at 10 s intervals into a measurement and control module (CR10, Campbell Scientific, Inc., Logan, Utah). All measurements were recorded as the average of output over the 10 s intervals.

To assess and ensure the integrity of the dynamic emissions measurement system, CO_2 recovery tests with 100% ethanol ($\text{C}_2\text{H}_5\text{OH}$) lamps were conducted prior to the beginning of the experiment and repeated every other week, as performed by Ning (2008). In the test, an alcohol lamp containing 100% ethanol was placed on the manure pan electronic balance in each chamber so that the dynamic as well as cumulative alcohol consumption could be obtained from the weight changes. The algorithms for the recovery test followed those by Scott and Hillman (1983).

The system was setup and handled in a way that would mimic a manure-belt housing system with a 6-day MAT so that the results of the study could be applicable to that housing type. The majority (>90%) of new laying-hen houses built in the U.S. nowadays are of manure-belt style, as opposed to the traditional high-rise style, because manure-belt houses have been proven to provide the hens with better air quality and lower emissions (Xin et al., 2011).

BIRD HANDLING AND EXPERIMENTAL DESIGN

The Hy-Line W-36 pullets/hens used in this study were procured from a commercial farm in Iowa. Two batches of 32 randomly assigned pullets (two weeks apart in age) at an initial age of 2 weeks were acquired in the beginning of the experiment. Twenty-eight of the 32 pullets in each batch were randomly allotted to the four cages or chambers, two cages or chambers with eight birds in each and the other two cages or chambers with six birds in each, thereby yielding two SDs: low density (LD) and high density (HD). The four remaining birds were housed separately in a hold-

ing cage for replacement of the test birds in case of mortality. After 12 days of measurement, the pullets inside the emission chambers were returned to the holding cages at the same SD as that used during the measurement. The following 2 days were used to check, calibrate, and perform maintenance on the instruments and prepare the system for the next trial. Then 28 pullets from the second batch (now having reached the same measurement age as those in the first batch) were allotted to the emission chambers to repeat the measurement. After two more weeks, the birds from the first batch were measured again. This procedure was repeated until the birds from the second batch reached 18 weeks of age.

For this study, a chamber or cage containing a group of birds under a specific SD and age was an experimental unit (EU). Thus, for the pullet portion of the experiment, two EUs were tested at the same time, and the two batches of pullets resulted in four replicates per treatment. For the layer portion of the experiment, the two previous batches were used when the hens were 23 weeks of age. However, to improve the statistical power of the results, two batches of ten hens each at an initial age of 34 weeks from the same farm were acquired and measured. Hence, for birds age 34 weeks and older, there was a total of eight replicates per treatment. All the birds were kept at the thermoneutral conditions of 21.1°C to 23.3°C and 40% to 50% RH, as suggested by the Hy-Line commercial management guide (Hy-Line, 2009).

Birds of the same EU were weighed in groups once a week with an electronic scale (6000 g \pm 1 g, model ICS6X9a-A6, Mettler-Toledo, Columbus, Ohio). Detailed information about the pullets, layers, and the dietary N contents is shown in table 1.

Air mass flow rate per chamber was regulated to mimic the minimum ventilation rate for pullets or laying hens based on the maximum allowed air CO₂ level of 4000 ppm_v (Albright, 1990). For instance, for pullets and laying hens at 4 and 30 weeks of age, the airflow rate was kept at 9.4 and 17.6 air changes per hour (ACH), respectively.

Three types of feed were offered to the pullets, i.e., starter (1 day to 4 weeks of age), grower 1 (4 to 8 weeks of age), and grower 2 (9 to 18 weeks of age), while one type of feed was offered to the hens (layer feed, 19 weeks of age and up). Feed ingredients and composition differed according to the type, but they usually included the following: corn, soybean meal, limestone, fat, corn germ, meat and bone meal, salt, monocalcium phosphorus, possibly synthetic lysine and choline. All freshly prepared rations were procured from the same farm where the experimental pullets were obtained and delivered to the lab on a semi-weekly basis to make sure that they remained fresh. Feed older than 3 weeks was discarded, as recommended by the provider. During the test period, fresh feed was added to the feeders daily (usually between 10:00 and 12:00 h): pullets age 1 day to 10 weeks received 200 and 300 g under LD and HD, respectively, and hens >19 weeks of age received 400 and 500 g under LD and HD, respectively. Loading the feeders with a greater amount of feed was avoided to reduce wastage, while the minimum value was calculated based on the number of birds per cage and the daily rec-

Table 1. Bird body weight (mean \pm standard error of the mean) and feed crude protein (CP) content (HD = high stocking density, LD = low stocking density).

Bird Age (weeks)	Bird Body Weight (kg)		Feed CP Content (%)
	HD	LD	
4	0.22 \pm 0.017	0.22 \pm 0.017	19.0
5	0.30 \pm 0.014	0.30 \pm 0.018	19.0
6	0.35 \pm 0.006	0.35 \pm 0.009	19.0
8	0.58 \pm 0.015	0.59 \pm 0.012	19.0
9	0.67 \pm 0.025	0.70 \pm 0.022	17.5
10	0.76 \pm 0.016	0.78 \pm 0.013	17.5
12	1.00 \pm 0.024	1.01 \pm 0.022	17.5
13	1.03 \pm 0.033	1.05 \pm 0.025	17.5
14	1.02 \pm 0.018	1.06 \pm 0.017	15.5
16	1.15 \pm 0.01	1.17 \pm 0.02	15.5
17	1.18 \pm 0.07	1.19 \pm 0.02	17.0
18	1.25 \pm 0.06	1.23 \pm 0.01	17.5
23	1.46 \pm 0.02	1.35 \pm 0.04	17.5
24	1.48 \pm 0.01	1.48 \pm 0.06	17.5
25	1.48 \pm 0.04	1.50 \pm 0.10	17.5
34	1.49 \pm 0.02	1.53 \pm 0.11	17.5
35	1.51 \pm 0.08	1.53 \pm 0.11	17.5
36	1.54 \pm 0.01	1.56 \pm 0.08	17.5

ommended feed intake according to age plus 20% extra to accommodate potential wastage.

Fluorescent lighting was provided at an illumination intensity of 10 lux with a lighting program specified for Hy-Line pullets and laying hens (Hy-Line, 2009). Nipple drinkers were used to supply drinking water.

Manure pans consisted of aluminum foil trays (40.0 cm length \times 30.0 cm width \times 4.5 cm depth) covered with clear plastic liners. Once every 6-day MAT, the trays were replaced with clean trays. To make sure that most of the manure fell inside the manure pans, the sides of the tray were slightly spread to increase the collecting area of the tray. Considering that a small amount of manure still fell outside the manure pan, either on the chamber walls or floor, all chambers were cleaned once every 6-day MAT.

For birds at 4 to 6 weeks of age, HD and LD were, respectively, 155 and 206 cm² bird⁻¹ (24 and 32 in.² bird⁻¹), i.e., the LD birds had 33% more floor space. For birds at 6 to 18 weeks of age, HD = 310 cm² bird⁻¹ (48 in.² bird⁻¹) and LD = 413 cm² bird⁻¹ (64 in.² bird⁻¹), i.e., 33% more space. For birds at 23 weeks and older, HD = 413 cm² bird⁻¹ (64 in.² bird⁻¹) and LD = 620 cm² bird⁻¹ (90 in.² bird⁻¹). To achieve the respective SD levels, the number of birds per chamber or cage was eight for HD and six for LD for pullets at 4 to 6 weeks of age, but four birds for HD and three birds for LD for pullets from 6 to 18 weeks of age. For layers at 23 to 37 weeks of age, treatments consisted of three and two hens per cage for HD and LD, respectively.

To complete the randomization process and account for possible chamber effect on measurements, groups under the same treatment switched chambers on a weekly basis so that, by the end of the trial, all SD levels were run in all four chambers and all ages.

Because the layer portion of the study involved a considerable bird age range of 23 to 37 weeks, the data were first analyzed for age effect. The results showed no age effect in term of feed use, manure production rate, or NH₃ ER. Consequently, the data were pooled over the age span of the layers.

CALCULATION OF NH₃ ER AND EVALUATION OF SD EFFECT ON NH₃ EMISSIONS

Daily NH₃ ER (mg h⁻¹ hen⁻¹) was calculated for 1 to 6 days of MAT with the following equation:

$$\text{NH}_3 \text{ ER} = \frac{Q_{STPD} \times (C_e - C_i) \times W_m \times 10^3}{10^6 \times V_m \times N} \quad (1)$$

where

Q_{STPD} = airflow rate at standard temperature (0°C), pressure (1 atm), and dry basis (L h⁻¹ chamber⁻¹)

C_e and C_i = exhaust and inlet NH₃ volumetric concentrations, respectively (ppm_v)

W_m = molecular weight of NH₃ (17.031 g mol⁻¹)

V_m = molar volume of NH₃ at standard temperature (0°C) and pressure (1 atm) (22.4 L mol⁻¹)

N = number of hens per cage or chamber.

NH₃ ER was expressed in different units, including mg bird⁻¹ d⁻¹, g AU⁻¹ d⁻¹ (AU = animal unit = 500 kg live body weight), g kg⁻¹ feed N use, and g kg⁻¹ as-is or dry basis manure. The feed N use was calculated from the feed use and crude protein (CP, table 1) content of the diet that was provided to us by the laying-hen farm. CP content was divided by 6.25 to yield the feed N content. Effects of SD were tested on a daily basis using *proc glm* in SAS. In addition, the percentage difference in mean ER values between the SD levels was calculated using the following equation:

$$\hat{\lambda} = \left(\frac{\hat{\mu}_{LD} - \hat{\mu}_{HD}}{\hat{\mu}_{HD}} \right) \times 100 \quad (2)$$

where

$\hat{\lambda}$ = estimated mean percentage difference (%)

$\hat{\mu}_{LD}$ = estimated mean value for the LD treatment

$\hat{\mu}_{HD}$ = estimated mean value for the HD treatment.

STATISTICAL ANALYSES

Statistical analysis was performed using SAS (version 6.2, SAS Institute, Inc., Cary, N.C.). Data modeling was performed in two different levels. The first, referred to as the full model, examined the effects of all possible factors and interactions (SD, MAT, and bird age) on the analyzed variables; the second, referred to as the reduced model, only considered the effect of SD. In the full model, the datasets were tested for normality through analysis of the plot of residuals (Ramsey and Schafer, 2002), and the results indicated the need for a log transformation. The log-transformed data were subjected to ANOVA with *proc mixed* and *proc glmix* in SAS. To more closely examine the SD effect on the response variables, the reduced model compared only the means for different SDs at a given bird age and MAT. The analysis of the plot of residuals indicated that, for a specific bird age and MAT, the variance was approximately constant, which allowed the datasets to be analyzed in the original scale. This was done using *proc glm* in SAS. A difference with a p-value of ≤0.05 was considered significant.

RESULTS AND DISCUSSION

EFFECTS OF BIRD AGE, MAT, AND SD ON NH₃ EMISSIONS: FULL MODEL ANALYSIS

The p-values obtained from the ANOVA indicated that bird age had a significant impact on feed use, as-is (fresh) or dry manure production, and NH₃ emissions (p < 0.0023). This outcome was expected because birds eat more as they grow (fig. 1a), increasing production of manure, which is the primary source of NH₃ emissions. The results of ANOVA for the full model also showed that as-is and dry manure weights were both significantly affected by MAT; consequently, NH₃ emissions in all units were significantly affected by MAT (p < 0.0001).

However, the full model analysis did not show a significant effect of SD on daily NH₃ ER (mg hen⁻¹ d⁻¹). Nevertheless, SD and MAT showed interaction with each other (p = 0.0057); hence, data for different SD were treated separately for assessment of the functional relationship of NH₃ ER with age and MAT. NH₃ ER was related to age and MAT with the following exponential equations (p < 0.0001):

For HD:

$$\text{NH}_3 \text{ ER} = e^{[(-36 \pm 14) + (5.2 \pm 0.6)\text{Age} + (2.8 \pm 0.8)\text{MAT}]} \quad (3)$$

(R² = 0.51)

For LD:

$$\text{NH}_3 \text{ ER} = e^{[(-30 \pm 11) + (3.7 \pm 0.5)\text{Age} + (4.2 \pm 1.2)\text{MAT}]} \quad (4)$$

(R² = 0.56)

where

NH₃ ER = daily NH₃ emission rate (mg hen⁻¹ d⁻¹)

Age = bird age (weeks)

MAT = manure accumulation time (d).

A more detailed examination of SD effect on NH₃ ER was conducted for different MAT in the reduced model, as described below.

EFFECTS OF SD ON NH₃ EMISSIONS:

REDUCED MODEL ANALYSIS

The downside of analyzing the datasets through the full model is that if the analysis was performed on the log-transformed scale, converting the standard error (SE) back to the original scale is complex (Ramsey and Schafer, 2002), and the direct transformation of SE from the logarithmic to the original scale is not recommended because it will overestimate the SE (Olsson, 2005). Thus, a simplified or reduced model was developed in which age and MAT were set constant, and the data were tested only for SD effect. The “unequal distribution” problem is eliminated here because the analysis is performed on subsections of the entire dataset.

There was no significant difference (p = 0.61 to 0.92) in either feed or feed N use between the two SD regimens for all bird ages or different MAT. This outcome indicates that the reduced floor space allocation did not adversely affect

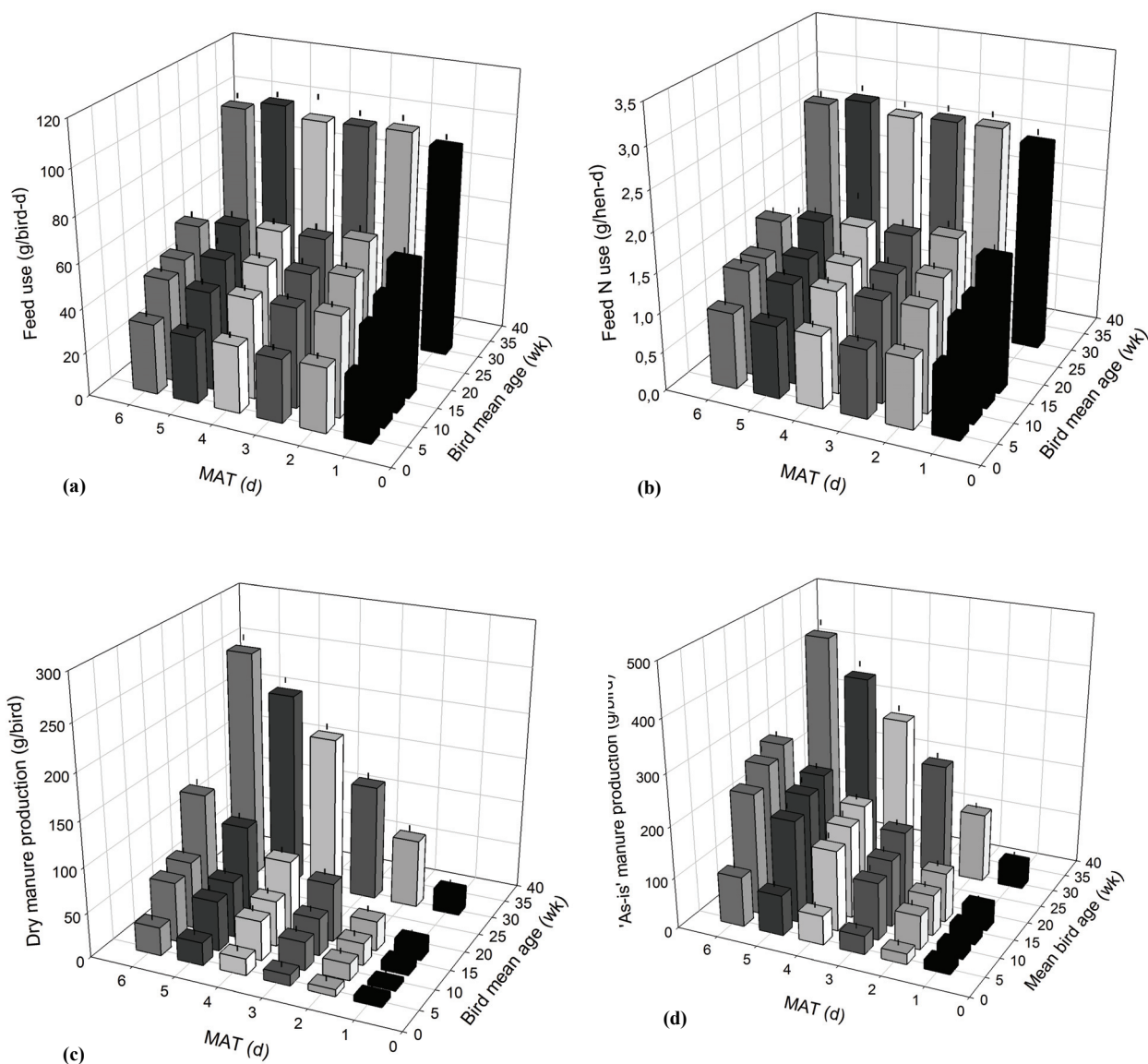


Figure 1. (a) Daily feed use, (b) daily feed N use, (c) as-is manure production, and (d) dry manure production of W-36 pullets/hens as a function of bird age (5 to 30 weeks) and manure accumulation time (MAT, 1 to 6 d). Vertical lines above data bars represent standard errors of the mean.

feed use. Figure 1 illustrates how feed use increased according to bird age but remained relatively constant within the 6-day cycles.

As-is manure weight data showed some significant effect of SD ($p = 0.03$), with HD having higher manure weight. The difference presumably arose from greater moisture evaporation for the LD manure because of larger exposed surface area per unit weight of manure. The larger number of birds under HD was also associated with a higher indoor RH, e.g., averaging 44% as compared to 37% in LD for the 8-week trials. The lower RH and greater vapor pressure gradient between the manure surface and the ambient air in LD would be more conducive to moisture loss of the manure. Manure moisture content (MC), determined from samples collected at the last day of the 6-day MAT, was lower for the LD manure ($p = 0.009$ to 0.04). The

overall MC averaged 74% for HD manure and 70% for LD manure (fig. 2). As-is and dry manure weight data as a function of MAT and bird age are illustrated in figures 1c and 1d.

Daily NH_3 ER data are presented in figure 3, while data for NH_3 ER in other units are reported in tables 2 through 6. When looking at SD effect on NH_3 ER, one can observe that the percentage differences between LD and HD were mostly negative for $\text{MAT} \geq 3$ days in all units of ER, suggesting that HD (smaller space allocation per bird) led to increased NH_3 emissions. Percentage difference values of SD effect on daily NH_3 ER were not calculated for $\text{MAT} < 2$ days (tables 2 to 5) because NH_3 concentrations and emissions for the earlier days were very low (< 1 ppm). Accordingly, the relative differences in NH_3 ER in all other units were also omitted for $\text{MAT} < 2$ days.

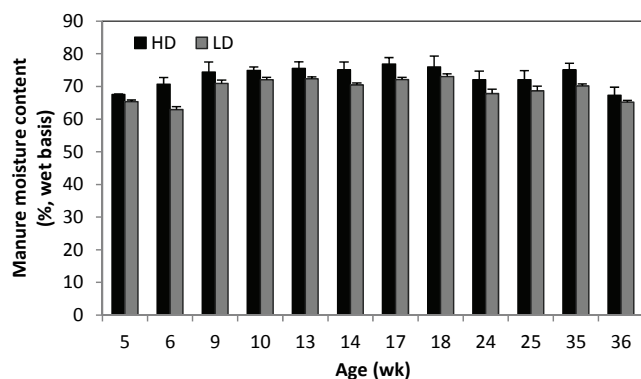


Figure 2. Moisture content of W-36 pullet/layer manure on the 6-day manure accumulation time (MAT) with high (HD) or low (LD) stocking density. Vertical bars represent standard errors of the mean.

The very small daily NH_3 ER values during the first two days of MAT were attributed to the thorough cleaning of the chambers at the end of each 6-day cycle. According to Li (2006), fresh layer manure takes 2 to 3 days of storage under favorable conditions for NH_3 to form and volatilize.

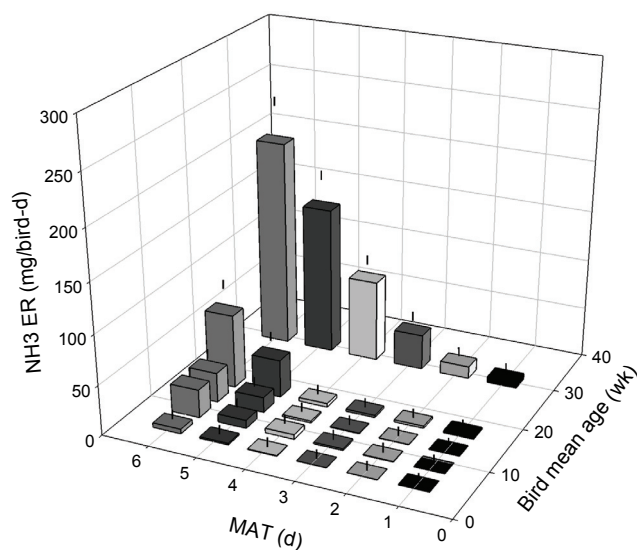


Figure 3. Daily NH_3 ER of W-36 pullets/hens as a function of bird age (5 to 30 weeks) and manure accumulation time (MAT, 1 to 6 d). Vertical lines above data bars represent standard errors of the mean.

Table 3. Ammonia emission of W-36 pullets over 6-day period at two stocking densities: bird age = 8 to 9 weeks; body weight = 580 to 670 g.

Variable and Stocking Density ^[a]		Manure Accumulation Time (MAT) ^[b]						Overall
		1 Day	2 Days	3 Days	4 Days	5 Days	6 Days	
Daily NH_3 emission ($\text{mg hen}^{-1} \text{d}^{-1}$)	HD	0.3 ± 0.4	0.6 ± 0.4	2 ± 1	5 ± 3	11 ± 5	30 ± 6	-
	LD	0.1 ± 0.4	0.2 ± 0.4	1 ± 1	4 ± 3	5 ± 5	26 ± 6	-
	% Diff.	-	-	-50	-20	-55	-13	-34
NH_3 emission ($\text{g kg}^{-1} \text{feed N use}$)	HD	0.24 ± 0.40	0.5 ± 0.3	1.6 ± 1	4 ± 4	9 ± 8	23 ± 8	-
	LD	0.08 ± 0.40	0.1 ± 0.3	0.7 ± 1	3 ± 4	4 ± 8	19 ± 8	-
	% Diff.	-	-	-53	-25	-58	-15	-38
NH_3 emission ($\text{g kg}^{-1} \text{manure, as-is}$)	HD	$0.013 \pm 0.002 \text{ b}$	0.008 ± 0.008	0.016 ± 0.005	0.03 ± 0.01	0.05 ± 0.02	0.12 ± 0.02	-
	LD	$0.004 \pm 0.002 \text{ a}$	0.003 ± 0.008	0.010 ± 0.005	0.03 ± 0.01	0.03 ± 0.02	0.12 ± 0.02	-
	% Diff.	-	-	-39	-2	-45	1	-21
NH_3 emission ($\text{g kg}^{-1} \text{manure, dry basis}$)	HD	0.02 ± 0.34	0.01 ± 0.03	0.06 ± 0.02	0.11 ± 0.05	0.2 ± 0.1	0.5 ± 0.1	-
	LD	0.06 ± 0.34	0.03 ± 0.03	0.03 ± 0.02	0.09 ± 0.05	0.1 ± 0.1	0.4 ± 0.1	-
	% Diff.	-	-	-48	-16	-54	-14	-33
NH_3 emission ($\text{g AU}^{-1} \text{d}^{-1}$)	HD	0.22 ± 0.30	0.4 ± 0.3	1.5 ± 0.8	4 ± 2	8 ± 4	22 ± 5	-
	LD	0.07 ± 0.30	0.1 ± 0.3	0.7 ± 0.8	3 ± 2	4 ± 4	19 ± 5	-
	% Diff.	-	-	-50	-20	-55	-13	-35

[a] HD = $310 \text{ cm}^2 \text{bird}^{-1}$, LD = $413 \text{ cm}^2 \text{bird}^{-1}$, and AU = animal unit = 500 kg live body weight.

[b] Values are means \pm standard error of the mean. Values of each variable for the two stocking densities followed by different letters are significantly different ($p \leq 0.05$). Daily NH_3 ER values for 1 and 2 days of MAT were rather small and close to the detection level of the measurement system; consequently, percentage difference (% Diff.) values were considered unreliable and omitted from presentation.

Table 2. Ammonia emission of W-36 pullets over 6-day period at two stocking densities: bird age = 4 to 5 weeks; body weight = 220 to 329 g.

Variable and Stocking Density ^[a]		Manure Accumulation Time (MAT) ^[b]						Overall
		1 Day	2 Days	3 Days	4 Days	5 Days	6 Days	
Daily NH_3 emission ($\text{mg hen}^{-1} \text{d}^{-1}$)	HD	0.05 ± 0.07	0.10 ± 0.18	0.27 ± 0.1	0.6 ± 0.2	2 ± 1	6 ± 2	-
	LD	0.02 ± 0.07	0.05 ± 0.18	0.14 ± 0.1	0.3 ± 0.2	1 ± 1	3 ± 2	-
	% Diff.	-	-	-50	-50	-44	-50	-48
NH_3 emission ($\text{g kg}^{-1} \text{feed N use}$)	HD	0.05 ± 0.07	0.11 ± 0.05	0.3 ± 0.1	0.6 ± 0.2	2 ± 1	6 ± 2	-
	LD	0.02 ± 0.07	0.06 ± 0.05	0.2 ± 0.1	0.3 ± 0.2	1 ± 1	3 ± 2	-
	% Diff.	-	-	-46	-48	-46	-53	-48
NH_3 emission ($\text{g kg}^{-1} \text{manure, as-is}$)	HD	0.003 ± 0.002	0.004 ± 0.003	0.007 ± 0.003	0.010 ± 0.004	0.02 ± 0.007	0.06 ± 0.02	-
	LD	0.002 ± 0.002	0.003 ± 0.003	0.004 ± 0.003	0.006 ± 0.004	0.01 ± 0.007	0.03 ± 0.02	-
	% Diff.	-	-	-44	-40	-30	-39	-38
NH_3 emission ($\text{g kg}^{-1} \text{manure, dry basis}$)	HD	0.007 ± 0.011	0.02 ± 0.20	0.02 ± 0.01	0.03 ± 0.02	0.07 ± 0.03	0.2 ± 0.1	-
	LD	0.003 ± 0.011	0.01 ± 0.20	0.01 ± 0.01	0.02 ± 0.02	0.04 ± 0.03	0.1 ± 0.1	-
	% Diff.	-	-	-56	-49	-44	-52	-50
NH_3 emission ($\text{g AU}^{-1} \text{d}^{-1}$)	HD	0.09 ± 0.10	0.2 ± 0.40	0.5 ± 0.5	1.0 ± 0.6	3 ± 1	10 ± 4	-
	LD	0.03 ± 0.10	0.09 ± 0.40	0.2 ± 0.5	0.5 ± 0.6	2 ± 1	5 ± 4	-
	% Diff.	-	-	-50	-50	-44	-50	-48

[a] HD = $310 \text{ cm}^2 \text{bird}^{-1}$, LD = $413 \text{ cm}^2 \text{bird}^{-1}$, and AU = animal unit = 500 kg live body weight.

[b] Values are means \pm standard error of the mean. Daily NH_3 ER values for 1 and 2 days of MAT were rather small and close to the detection level of the measurement system; consequently, percentage difference (% Diff.) values were considered unreliable and omitted from presentation.

Table 6. Ammonia emission of W-36 hens over 6-day period at two stocking densities: bird age = 23 to 36 weeks; body weight = 1351 to 1564 g.

Variable and Stocking Density ^[a]		Manure Accumulation Time (MAT) ^[b]						Overall
		1 Day	2 Days	3 Days	4 Days	5 Days	6 Days	
Daily NH ₃ emission (mg hen ⁻¹ d ⁻¹)	HD	5 ±3	12 ±4	41 ±9	98 ±13	179 ±26	251 ±33	-
	LD	7 ±3	12 ±4	29 ±9	64 ±13	114 ±26	160 ±33	-
	% Diff.	3	1	-31	-34	-36	-36	-22
NH ₃ emission ^[c] (g kg ⁻¹ feed N use)	HD	2 ±1	4 ±1	16 ±3	40 ±4 a	61 ±11	105 ±11 a	-
	LD	2 ±1	4 ±1	11 ±3	24 ±4 b	42 ±11	62 ±11 b	-
	% Diff.	7	3	-35	-38	-32	-40	-22
NH ₃ emission ^[c] (g kg ⁻¹ manure, as-is)	HD	0.07 ±0.05	0.1 ±0.02	0.15 ±0.02	0.30 ±0.03	0.42 ±0.04	0.52 ±0.06	-
	LD	0.07 ±0.05	0.1 ±0.02	0.12 ±0.02	0.22 ±0.03	0.30 ±0.04	0.35 ±0.06	-
	% Diff.	6	8	-17	-25	-29	-33	-15
NH ₃ emission ^[c] (g kg ⁻¹ manure, dry basis)	HD	0.10 ±0.07	0.12 ±0.04	0.27 ±0.04	0.52 ±0.05	0.8 ±0.1	0.9 ±0.1	-
	LD	0.15 ±0.07	0.10 ±0.04	0.20 ±0.04	0.35 ±0.05	0.5 ±0.1	0.6 ±0.1	-
	% Diff.	-33	17	-27	-33	-30	-32	-23
NH ₃ emission ^[c] (g AU ⁻¹ d ⁻¹)	HD	2 ±1	4 ±1	14 ±3	32 ±4	58 ±8	82 ±10	-
	LD	2 ±1	4 ±1	9 ±3	20 ±4	36 ±8	51 ±10	-
	% Diff.	8	6	-34	-37	-38	-37	-22

^[a] HD = 413 cm² bird⁻¹, LD = 620 cm² bird⁻¹, and AU = animal unit = 500 kg live body weight.

^[b] Values are means ± standard error of the mean. Values of each variable for the two SDs followed by different letters are significantly different (p ≤ 0.05). Percentage difference (% Diff.) uses LD as basis.

^[c] NH₃ emissions calculated using "clean" system NH₃ ER data.

Table 4. Ammonia emission of W-36 pullets over 6-day period at two stocking densities: bird age = 12 to 13 weeks; body weight = 1000 to 1030 g.

Variable and Stocking Density ^[a]		Manure Accumulation Time (MAT) ^[b]						Overall
		1 Day	2 Days	3 Days	4 Days	5 Days	6 Days	
Daily NH ₃ emission (mg hen ⁻¹ d ⁻¹)	HD	0.3 ±0.2	0.3 ±0.1	1.0 ±0.1 a	3 ±1	16 ±4	36 ±8	-
	LD	0.1 ±0.2	0.1 ±0.1	0.6 ±0.1 b	2 ±1	14 ±4	23 ±8	-
	% Diff.	-	-	-45	-33	-13	-36	-32
NH ₃ emission (g kg ⁻¹ feed N use)	HD	0.2 ±0.2	0.2 ±0.2	0.7 ±0.2	2 ±2	11 ±4	28 ±9	-
	LD	0.1 ±0.2	0.1 ±0.2	0.4 ±0.2	1 ±2	10 ±4	16 ±9	-
	% Diff.	-	-	-39	-37	-11	-41	-32
NH ₃ emission (g kg ⁻¹ manure, as-is)	HD	0.008 ±0.010	0.004 ±0.010	0.007 ±0.010	0.02 ±0.02	0.06 ±0.02	0.12 ±0.03	-
	LD	0.003 ±0.010	0.001 ±0.010	0.005 ±0.010	0.01 ±0.02	0.07 ±0.02	0.010 ±0.03	-
	% Diff.	-	-	-36	-20	10	-21	-17
NH ₃ emission (g kg ⁻¹ manure, dry basis)	HD	0.025 ±0.03	0.013 ±0.03	0.028 ±0.04	0.064 ±0.03	0.28 ±0.06	0.5 ±0.1	-
	LD	0.009 ±0.03	0.004 ±0.03	0.012 ±0.04	0.037 ±0.03	0.21 ±0.06	0.3 ±0.1	-
	% Diff.	-	-	-58	-42	-23	-43	-41
NH ₃ emission (g AU ⁻¹ d ⁻¹)	HD	0.15 ±0.04	0.15 ±0.04	0.49 ±0.05 a	1.47 ±0.05 a	7.82 ±0.06 a	17.6 ±0.1 a	-
	LD	0.05 ±0.04	0.05 ±0.04	0.27 ±0.05 b	0.98 ±0.05 b	6.84 ±0.06 b	11.2 ±0.1 a	-
	% Diff.	-	-	-45	-33	-13	-36	-32

^[a] HD = 310 cm² bird⁻¹, LD = 413 cm² bird⁻¹, and AU = animal unit = 500 kg live body weight.

^[b] Values are means ± standard error of the mean. Values of each variable for the two stocking densities followed by different letters are significantly different (p ≤ 0.05). Percentage difference (% Diff.) uses LD as basis. Daily NH₃ values for 1 and 2 days of MAT were rather small and close to the detection level of the measurement system; consequently, percentage difference values were considered unreliable and omitted from presentation.

Table 5. Ammonia emission of W-36 pullets over 6-day period at two stocking densities: bird age = 16 to 17 weeks; body weight = 1015 to 1018 g.

Variable and Stocking Density ^[a]		Manure Accumulation Time (MAT) ^[b]						Overall
		1 Day	2 Days	3 Days	4 Days	5 Days	6 Days	
Daily NH ₃ emission (mg hen ⁻¹ d ⁻¹)	HD	2.00 ±0.03	2.4 ±0.1 a	2.4 ±0.2	5 ±2	49 ±13	90 ±21	-
	LD	2.03 ±0.03	1.8 ±0.1 b	1.9 ±0.2	2 ±2	26 ±13	57 ±21	-
	% Diff.	1	-23	-21	-60	-47	-37	-31
NH ₃ emission ^[c] (g kg ⁻¹ feed N use)	HD	1.13 ±0.03 a	1.28 ±0.07 a	1.3 ±0.1	2.9 ±1	28 ±9	56 ±16	-
	LD	1.27 ±0.03 b	0.98 ±0.07 b	1.1 ±0.1	1.1 ±1	15 ±9	33 ±16	-
	% Diff.	12	-23	-14	-62	-46	-41	-41
NH ₃ emission ^[c] (g kg ⁻¹ manure, as-is)	HD	0.044 ±0.001	0.023 ±0.001	0.016 ±0.00 1a	0.025 ±0.008	0.20 ±0.05	0.30 ±0.08	-
	LD	0.044 ±0.001	0.020 ±0.001	0.011 ±0.001 b	0.010 ±0.008	0.11 ±0.05	0.20 ±0.08	-
	% Diff.	-1	-14	-32	-60	-47	-36	-44
NH ₃ emission ^[c] (g kg ⁻¹ manure, dry basis)	HD	0.09 ±0.05 a	0.06 ±0.01	0.035 ±0.02	0.06 ±0.03	0.4 ±0.2	0.6 ±0.3	-
	LD	0.14 ±0.05 b	0.07 ±0.01	0.034 ±0.02	0.03 ±0.03	0.2 ±0.2	0.4 ±0.3	-
	% Diff.	56	16	-2	-54	-35	-27	-8
NH ₃ emission ^[c] (g AU ⁻¹ d ⁻¹)	HD	0.87 ±0.02	1.03 ±0.08	1.0 ±0.1	2.2 ±0.5	21 ±9	39 ±16	-
	LD	0.88 ±0.02	0.79 ±0.08	0.8 ±0.1	0.9 ±0.5	11 ±9	25 ±16	-
	% Diff.	1	-23	-21	-60	-47	-37	-41

^[a] HD = 310 cm² bird⁻¹, LD = 413 cm² bird⁻¹, and AU = animal unit = 500 kg live body weight.

^[b] Values are means ± standard error of the mean. Values of each variable for the two stocking densities followed by different letters are significantly different (p ≤ 0.05). Percentage difference (% Diff.) uses LD as basis.

^[c] NH₃ emissions calculated using "clean" system NH₃ ER data.

Percentage differences in NH_3 ER at different SDs were calculated for MAT ≥ 3 days even when statistical significance did not exist because the full model analysis revealed interactions between SD and MAT ($p = 0.0057$). It can be noted that a significant effect of SD was detected on the third day of MAT for pullets at 12 weeks of age: $1.0 \pm 0.1 \text{ mg hen}^{-1} \text{ d}^{-1}$ for HD vs. $0.6 \pm 0.1 \text{ mg hen}^{-1} \text{ d}^{-1}$ for LD (table 4). The increased variance in NH_3 ER at longer MAT was likely responsible for the lack of significance of the SD effect, which might have been partially remedied by increasing the number of treatment replications. One can infer from tables 2 through 6 that the overall negative percentage difference values generally decrease with increasing bird age. For instance, the percentage difference in NH_3 ER (in $\text{mg hen}^{-1} \text{ d}^{-1}$) between LD and HD was -48% for pullets at 4 to 5 weeks of age and -22% for hens at 23 to 36 weeks of age. The results also indicate that, regardless of the SD level, daily NH_3 ER increased considerably for MAT > 4 days. This outcome supports the current management practices used in manure-belt laying-hen housing systems, where manure is usually removed at 1 to 3 days of MAT primarily to avoid overloading the belts (Xin et al., 2011, personal communication) and also has the benefit of reduced house-level NH_3 generation and emission.

Liang et al. (2005) measured NH_3 ER from manure-belt laying hen houses with MAT = 1 day (Iowa) or 3 to 4 days (Pennsylvania) and reported that the overall NH_3 ER was $54 \pm 5 \text{ mg hen}^{-1} \text{ d}^{-1}$ for MAT = 1 day and $94 \pm 2 \text{ mg hen}^{-1} \text{ d}^{-1}$ for MAT = 4 days. The ER value for 4-day MAT parallels that observed in the current study (64 to $98 \text{ g hen}^{-1} \text{ d}^{-1}$, table 6). However, the ER values for MAT of 1 to 3 days in the current study were considerably lower than that reported by Liang et al. (2005). The discrepancies presumably arose from the fact that, in the current study, all the chambers were totally cleaned (the existing manure pans were replaced with new ones) after each trial, whereas in a production setting there is inevitably some manure residue on the belt, which would contribute to higher NH_3 emissions.

Ammonia ER in other units followed similar trends to that of ER in $\text{g hen}^{-1} \text{ d}^{-1}$ (tables 2 through 6). The overall percentage difference in g NH_3 emissions per kg feed N use varied from -8% to -50%, depending on bird age.

SD effects on NH_3 emissions in g kg^{-1} manure were similar for manure expressed in as-is and dry basis for most days of MAT. Ammonia emissions under LD were 17% to 44% lower than those under HD in g kg^{-1} as-is manure, and 8% to 50% lower in g kg^{-1} dry manure.

CONCLUSIONS

Effects of pullet and laying-hen age, manure accumulation time (MAT), and stocking density (SD) on ammonia (NH_3) emission were examined using environmentally controlled emissions chambers. MAT ranged from 1 to 6 days. At every tested bird age, two levels of SD were applied, with one level having 33% more space allocation for the birds (denoted as low density or LD) than the other (denoted as high density or HD). The following conclusions were drawn:

- NH_3 emission increased with bird age and MAT, following an exponential pattern.
- The LD regimen resulted in 22% to 48% lower NH_3 emissions than the HD regimen on per-bird basis, depending on bird age.
- Daily NH_3 ER increased considerably for MAT > 4 days.

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